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Starch molecular structure: The basis for an improved understanding of cooked rice texture

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ABSTRACT

Much is known about factors affecting rice texture, but the underlying molecular reasons for the observations are less well understood. Cooked rice displays multiple textural attributes, of which the major ones are hardness and stickiness. A unified molecular mechanistic description of the cause of these two textural attributes is summarized. Amylose molecules may entangle and/or co-crystallize with amylopectin chains in the crystalline lamellae, thereby causing limited starch swelling during rice cooking and a harder texture. An increase of the amount of amylopectin, the proportion of short amylopectin chains, and amylopectin molecular size in the leachate during cooking, create a greater opportunity for bonding and molecular interaction, causing more force to be needed to make the grains come apart, i.e. a higher stickiness. This improved understanding of rice texture will help rice breeders, rice industry and consumers to manage and improve the cooking and eating quality of cooked white rice.

1. Introduction

Rice is one of the most important staple foods for human consumption. More than 90% of rice is grown and consumed in South, East, and Southeast Asia, where ~60% of the world's population lives (Bhattacharya, 2009). With the high levels of economic growth in Asia over the past thirty years lifting hundreds of millions of people out of poverty to the middle class, the demand for higher quality rice is rapidly increasing (Lee & Hong, 2012). Rice consumers in different countries and regions, particularly from countries for which rice is the staple, have strong and often different preferences regarding the sensory (mouth-feel, "taste") properties of rice (Champagne et al., 2010). An emerging challenges facing the rice industry and breeders is to control the eating quality of rice for specific end-use markets. Cooked rice texture is the main factor governing the acceptance of rice by consumers (Okabe, 1979).

Rice is the only major cereal that is consumed mostly in the form of whole grains after cooking. In general, rice is classified into the following groups by amylose content: waxy (0–2%), very low (3–9%), low (10–19%), intermediate (20–25%) and high (> 25%). Cooked rice texture is affected by a wide range of factors, such as the amylose content (Juliano, Onate, & Del Mundo, 1972), postharvest processing (Champagne et al., 1998), the milling ratio (Lyon et al., 1999; Park, Kim, & Kim, 2001), general type (waxy, indica, japonica) and the cooking method (Leelayuthsoontorn & Thipayarat, 2006). Polished white rice is the most widely consumed form, while unmilled brown rice is only eaten in some cultures (Kaur, Ranawana, & Henry, 2016). This review focusses on the texture of cooked white rice. The emphasis is on the molecular structural features (including amylose content) controlling texture. The various factors alluded to above (processing, type, etc.) control this structure, but are not the factors directly controlling textural attributes.

Food texture is a multidimensional characteristic that only humans can truly perceive and define (Chen, 2009; Szczesniak, 1987). As rice breeders and the rice industry prefer to judge rice quality using approaches that are less costly and less time-consuming than human panels, considerable effort has been expended to develop instrumental measurements to provide mechanistic insights into the texture of cooked rice (Champagne et al., 1999; Meullenet, Champagne, Bett, McClung, & Kauffmann, 2000; Sesmat & Meullenet, 2001). However, these cannot mimic the whole oral processing of cooked rice, and imperfectly reflect the human-perceived textural attributes. It is important to understand the internal relations between all these textural attributes and find the main attributes governing the consumer acceptance.

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Furthermore, since starch accounts for up to 95% of rice dry weight (Fitzgerald, McCouch, & Hall, 2009), but variations of starch content between different rice cultivars are not significantly different (Li, Prakash, Nicholson, Fitzgerald, & Gilbert, 2016a), it would be beneficial to learn the molecular mechanisms of these important textural attributes, especially those due to starch molecular structure. This knowledge will assist rice researchers to unlock the relations between starch structure and rice texture and help rice breeders, rice industry and consumers to manage and improve the cooking and eating quality of cooked white rice.

Cooked white rice is a particularly good subject to understand the relations between sensory (consumer acceptance) and molecular structure. This is because in its most commonly consumed form, it is quite a simple food: mainly starch and water, with smaller amounts of other components. This makes it perhaps the easiest staple food to carry out such investigations. The basic precepts for this simple but common food can then serve as a basis for corresponding investigations for other important but more complex foods.

2. Textural attributes of cooked rice

Brandt, Skinner, and Coleman (1963) defined a texture profile as "the sensory analysis of the texture complex of a food in terms of its mechanical, geometrical, fat and moisture characteristics, the degree of each present and the order in which they appear from first bite through complete mastication." Further interest in a detailed descriptive method developed as a result of the growth of new products and competition in the measurement and improved data processing systems (Stone, Sidel, Oliver, Woolsey, & Singleton, 1974; Stone & Sidel, 1998). A widely used terminology for the texture of cooked rice and other foods was developed in the late 1990s (Lyon et al., 1999; Lyon, Champagne, Vinyard, & Windham, 2000; Meullenet, Gross, Marks, & Daniels, 1998). The terms, including evaluation procedures and definitions of attributes, were clearly defined. The sensory texture profile included 16 sensory attributes that described rice texture at different phases of sensory evaluation, beginning with characteristics outside the mouth and ending with mouthfeel characteristics after rice was swallowed. Typical attribute terms are initial starchy coating, slickness, roughness, stickiness to lips, stickiness between grains, springiness, cohesiveness, hardness, uniformity of bite, cohesiveness of mass, moisture absorption, residual loose particles and toothpack. Rice texture displays a multi-dimensional and dynamic nature, as do other foods (Foegeding, Daubert, Drake, Essick, Trulsson, Vinyard & Van De Velde, 2011; Stokes, Boehm, & Baier, 2013). Since rice texture and mouthfeel are prominent attributes for consumer choice and acceptability, this section reviews factors, especially starch molecular structure, affecting textural attributes of cooked rice and the evaluation methods for this texture, and also the significance of the relations between starch structure and the two most important textural attributes (hardness and stickiness) of cooked white rice.

2.1. Factors affecting cooked rice texture

2.1.1. Postharvest processing conditions

Since rice is usually used and consumed as milled whole rice after removing the outer hull and the bran layers of the rough rice, the eating quality of rice can be affected by postharvest processing, including the drying conditions, the final moisture content and the degree of milling (DOM). The rice moisture content at harvest, an indicator of rice kernel development, is another important factor that affects rice quality (Wang, Siebenmorgen, Matsler, & Bautista, 2004). Postharvesting affects rice eating quality *indirectly*, because it can result in changes in the molecular structural characteristics that *directly* affect sensory properties. The emphasis of the present review is on starch structure. Discussion of various "indirect" factors (e.g. post-harvest processing) can be found elsewhere, for example, (Champagne, Bett-Garber, Thompson, Mutters, Grimm, & McClung, 2005; Juliano et al., 1984; Park et al., 2001).

2.1.2. Cooking methods

Rice is generally cooked and consumed whole (Marshall, 1993). Different countries or regions have different cooking protocols. Some cook rice in rice cookers: milled rice is washed with cold water followed by straining to remove excess water; after washing, rice is transferred to the rice cooker and water is added to give the appropriate water: rice ratio. One can also cook rice using a pan with excess water: rice is washed, added to three portions of water (w/w), soaked, and boiled. Another method to cook rice involves complete evaporation (Champagne et al., 2010). Most cooking methods are variations of two basic techniques: (i) cooking in large amounts of water, with subsequent drainage (and sometimes rinsing)—commonly referred to as the Excess or American method; or (ii) cooking of rinsed rice in a measured amount (often twice the volume of rice) of water which is absorbed into the rice—commonly known as the Pilaf or Oriental method (Sinki, 1994).

There are some emerging technologies for in rice cooking, such as microwave heating and high hydrostatic pressure (HHP) (Hayashi, 1991). In traditional rice cooking, the energy is transmitted from outside to inside, while in microwave heating, the energy is transmitted from the centre to the edge (Li, Han, Xu, Xiong, & Zhao, 2014). It was reported that a panel had equal preference for microwave-cooked rice varieties and rice cooked via the more traditional methods (Khatoon & Prakash, 2007), but that is by no means a universal result: many people find microwaved rice less palatable than that from other methods. HHP has been investigated as an alternative to the traditional thermal processing of foods. In HHP processing, applied pressure is instantaneously and uniformly distributed within the product, removing the influence of sample size on processing times. Boluda-Aguilar, Taboada-Rodríguez, López-Gómez, Marín-Iniesta, and Barbosa-Cánovas (2013) used HHP to cook rice rapidly, and found that rice which was processed with a single HHP treatment at 300 and 400 MPa had a better acceptance than that of other treatments; however, that favourable result is by no means always the case.

Parboiling is practiced widely in the South Asian region. The process of parboiling involves: 1) steeping the paddy in water until it is saturated (~30% moisture), 2) draining the water, 3) steaming or heating the soaked paddy to gelatinize the starch, and 4) drying the wet grains to the normal moisture content. Parboiling has a pronounced effect on the physical properties (shape, colour, hardness), flow and storage properties, chemical and nutritional properties, physicochemical properties, as well as the cooking and eating quality. For example, parboiled rice takes a longer time to cook than raw rice, and cooked parboiled rice is firmer than cooked raw rice (Ramesh, Bhattacharya, & Mitchell, 2000). It is suggested that the degradation of the structure of the starch granules during the heat treatment and starch retrogradation during the drying stage of the parboiling process are responsible for reduced starch swelling in parboiled rice, thereby causing a reduced stickiness of cooked rice (Damir, 1985). The process of parboiling can cause starch retrogradation (Ali & Bhattacharya, 2006; Derycke, Veraverbeke, Vandeputte, De Man, Hoseney & Delcour, 2005; Ramesh et al., 2000).

Among all these cooking methods, the amount of water added to the grain is one of the major factors that influence cooked-rice texture; basically, the rice-to-water weight ratio varies according to its amylose content, e.g. 1:1.3 for waxy rice, 1:1.6 for low- and intermediate-amylose rice and 1:1.8 for high-amylose rice (Bett-Garber, Champagne, Ingram, & McClung, 2007; Juliano & Perez, 1983). Grain stickiness increases when rice is cooked with increasing water to rice ratios (Kim & Kim, 1996). However when using the excess water method, the water content and stickiness were found to be unrelated (Juliano et al., 1984). Kim, Kim, and Kim (1986) found, using subjective means, that changes in water to rice ratios had an effect on texture and appearance. Srisawas